

Analysing renewable energy flow distribution and its influence on grid electricity prices

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Abstract. The paper presents an approach to the assessment of technical and economic efficiency for an electric energy (EE) transport in a distribution grid. It is focused on the extent of renewable energy sources (RES) integration efficiency according to energy prices in a grid. A two-step procedure for calculation is used in terms of the approach. The first one includes the obtaining of energy flows distribution in a grid. The next step provides the calculation of costs flows and nodal prices for electric energy. Both stages are performed using a developed branch flow model. Unlike power flow distribution describing the instant point of time, energy flow distribution developed for any operation duration deals with the integral values of the flows. This is of great importance for the deeply varying output profiles of the intermittent renewables. The model provides the direct utilization of electric energy meters data available in a grid. The approach presented is essential for locating the particular consumers of the renewable energy in terms of a grid's deep state and circuit diversity as well as for analyzing the influence of a renewable energy for electricity prices, and estimating the necessary renewables' levelised cost of energy (LCOE).

Key words. Power flow distribution, energy flow distribution, electric energy, LCOE, electricity prices.

1. Introduction

The steady-state parameters of a grid are typically obtained by carrying out the calculation of power flow distribution. It is conventionally performed using power flow equations based on the nodal voltages [1]. The power flow distribution describes the instant point of time. Due to the fact that persistent changes occur in power system, power flow distribution correctly represents the state in a grid when these changes are slow and their magnitude is insufficient. This feature limits the applicability of power flow distribution to short-time issues or to the issues concerned with the fit-and-forget approach, when the absolute minimum and maximum states are checked during power system design. Large power systems within relatively slow load changes of 3-5 % per hour historically enable the re-calculation of steady-state once in a hour

($T=1$ h), although modern distribution grid requires to make it once in several minutes $T=5-15$ min to represent the state correctly. In fact, a set of sequential non-correlated and non-interrelated states of a *fixed duration* is computed in this case [2], [3]. The calculation is suitable for basic dispatch, scheduling and market purposes. Nevertheless, there are the cases when conventional approaches and models undergo serious methodical violations restricting the application of power flow distribution:

- 1) *Due to the general nonlinearity* of electric circuits (Joule-Lenz law, resistance variations, etc.), averaging over T while deep and fast state changes occur leads to the strong qualitative errors in state representation [4]. The case is directly concerned with the intermittent renewables and low-voltage loads tending to rapid power fluctuations.
- 2) *Topology diversity* in grids of meshed structure and *reverse electrical energy flow* during T leads to qualitative errors in state representation besides the quantitative ones [5].
- 3) *The prospective planning* of any grid while considering the economic features to be based on some weighted and averaged parameters. There could be a set of the load curve profiles and generation output profiles available for the grid and their composition during the long periods is not always evident. A some integral estimation is needed.
- 4) *EE prices may not be constant* and vary at the commercial intervals that are not coincident with the dispatch intervals of fixed T .
- 5) *The problem of steady-state calculation using measurements data* is considered applying state estimation theory. For conventional state estimation, SCADA telemetry with quasi-instant power values is used. Energy management

systems to provide the EE values for several minutes or hours. At the level of low-voltage systems, especially if electricity measurements are manually gathered from non-smart meters, the interval can be a month or even a year.

- 6) Besides the time-scale problems, the models for power flow distribution are typically sensitive for a grid scale. Zero and close to zero resistances of branches complicate the formation of conductivity matrix and observation of the computation results.

Renewable energy sources usually are interconnected to distribution systems where all the listed problem features are typical and should be taken into account. The detailed analysis of energy utilization from a renewable energy source and its influence on a grid nodal prices requires more specified models providing stable calculation in terms of deep state, topology and time-scale diversity, like branch-flow models [6], [7]. In fact, recent studies about branch flow models are concerned with the computational algorithm itself [8]-[10], and not the sphere the model application like distribution systems, distributed generation and RES in particular.

The aim of the paper is to adapt a branch-flow model to economic estimation of the renewables efficiency integration into electric grid. The results of the estimation are suitable for billing, markets, and prospective planning of distribution systems development. The model is presented further.

2. Theoretical background

A. Energy flow distribution model

The model for energy flow distribution in a grid to possess the following features: integral, providing grid topology changes accounting, scale-insensitive for time and grid length. These features are mostly essential for the branch flow model described by Energy Flow Problem solution [11]-[13]. The main input data for the EFP are the measurements of active and (optional) reactive EE. The result of this problem solution is balanced EE flows and losses distribution at all the elements of the electrical grid called Energy Flow Distribution (EFD).

The equations for EFP based on the EE balance equations are set for all the nodes and the branches of a grid. The equations of the nodal EE balances are set separately for active and reactive flows:

$$\sum_{j \in \omega_i} W_{ij}^p + W_i^p + \Delta W_i^p = 0; \\ \sum_{j \in \omega_i} W_{ij}^q + W_i^q + \Delta W_i^q = 0, \quad i = 1, 2, \dots, N, \quad (1)$$

where W_i^p, W_i^q are the injections of active and reactive EE for node i ; W_{ij}^p, W_{ij}^q are active and reactive EE flows across all the branches between nodes i and j ; ω_i is the set of nodes incident to the node i ; $\Delta W_i^p, \Delta W_i^q$ are the losses of

active and reactive EE in the node i shunt; N - is the number of model nodes.

The balance of EE in the branches is determined by W_{ij} EE flow at the beginning of the branch, W_{ji} at its end, and by the EE losses ΔW_{ij} :

$$W_{ij}^p + W_{ji}^p + \Delta W_{ij}^p = 0; \\ W_{ij}^q + W_{ji}^q + \Delta W_{ij}^q = 0, \quad ij = 1, 2, \dots, M, \quad (2)$$

where M - is the number of model branches. The balance equations (1) - (1) form the basis of the EFP state equations and they are linear.

Modelling the losses is discussed in details in [13] making the problem formulation linear or nonlinear. The most popular approaches are decremental losses accounting for linear estimation and Joule-Lenz law calculation for non-linear iteration-based estimation.

The model provides the direct electricity meters measurements data utilization. Due to the fact that all the measurements contain errors because of the non-ideal accuracy of metering complexes, a state estimation approaches to be used for obtaining the balanced energy flow distribution [14]. The weighted sum of flows deviation squares is used multiplied by meters accuracy coefficients:

$$F = \sum_{i=1}^K \frac{1}{(\delta_i^{\%} \hat{W}_i)^2} (\hat{W}_i - W_i)^2 \rightarrow \min, \quad (3)$$

where \hat{W}_i is the measured value for each considered flow.

The advantages of the model proposed are:

- 1) *Energy flow distribution* can be calculated in a single procedure for any time interval.
- 2) *The equations of EE balances* don't have residuals due to grid state and topology variations over the time T , that is, they always retain the relevance to the simulation [15], [16].
- 3) *The flow-based model is insensitive to the scale of the equivalent circuit parameters.* The conductivity is not used in calculations. It is possible to calculate the circuits containing zero resistance of the branches. The last EFP advantage is very important, since it allows to introduce in the equivalent circuit some intersection circuit breakers that are often equipped with EE meters.
- 4) *Simplicity of the measurements' equations* provides the calculation approximately five times faster than SE using voltages [15], [16].

The limitations of the model include the necessity to know the particular duration of switch off mode for any circuit component. Otherwise, it may results in a sufficient garble in energy flows outlay. It could be controlled for the branches of a grid circuit where the metering data are available.

B. Cost flow distribution model

The idea of the cost flow distribution is that all the electric energy flows have cost depending upon electricity prices. Electricity prices depend upon power generation prices like $LCOE$ [17], [18], as well as transmission and distribution (T&D) prices. It is related to the set of market models [19]–[21] using the nodal prices, but has the following strong differences:

- 1) *The cost flow model based on the energy flow distribution* referred at *A* section of the paper. It is assumed that the energy flows for nodes and branches as well as losses are calculated by the energy flow model and can be considered as absolutely balanced flows. The values to be calculated for an analyzed time interval, for example one month or one year. If a time interval under investigation is a retrospective interval, then the data from energy meters to be used as a basis for the energy flow model. To the contrary, if a prospective is considered, than forecasted values of energy input and output to be used.
- 2) *The initial data can be presented directly by the capital costs* of grid construction, if necessary. Power generation prices and especially T&D prices are strongly influenced by the capital costs of their construction. Distinguishing grid market models provide that technical interconnection may be charged in a direct single-time payment or by the capital depreciation charges increasing the T&D price and the resulting nodal electricity price. Both types of the initial data can be mixed in the model [22], [23].

In the model presented the branches of a grid circuit are associated with power lines, nodes are associated with substations' buses. The model corresponds to process of EE transport in the form of directed energy flows graph and directed cost flow graph. The process of both energy and cost flows allocation to be performed using the same grid equivalent circuit. The idea of transport costs distribution implies a sequence of transferring power generation costs and T&D costs with respect to a path of EE flow direction in a grid graph. As a result, cost flows for each branch and each node can be calculated. It is useful to represent the process in the form of cost flows having the same direction as energy flows.

The nodal cost injections can be calculated as:

$$C_i = c_i W_i, \quad (4)$$

where c_i is the price of generation, W_i is the EE output value. The nodal cost can be calculated as:

$$C_{i\Sigma} = C_i + C_{ii}, \quad (5)$$

where C_i is the nodal cost injection and C_{ii} is the sum of the cost flows incoming to the node. Generally, the following cases are possible:

- 1) The node is an energy source node, then the flow inputs into the branches exporting the energy from the node proportionally to EE flows with respect to the total energy source output.
- 2) The node is a transit node of zero nodal injection, then the flow sum incoming the node distributes across the branches exporting the energy from the node proportionally to EE flows with respect to the transit nodal energy input.
- 3) The node is an terminal node of a radial grid. The nodal cost is equal to the sum of inflows.
- 4) The node is a transit node of non-zero nodal flow like energy source or load. Then the required nodal costs contain both nodal and transit flow components.

The nodal costs inflow into the adjacent branches proportionally to outcoming energy flows. Cost flow for the beginning of the branch adjacent to i node are calculated as:

$$C_{ij} = \frac{W_{ij}}{W_i + W_{ii}} \cdot \frac{1}{C_i + C_{ii}}, \quad (6)$$

where W_{ii} is the sum of EE flows in branches adjacent to the i node. The link between the cost at the beginning C_{ij} and the end C_{ji} of the branch:

$$C_{ji} = C_{ij} + \Delta C_{ij}, \quad (7)$$

where ΔC_{ij} is the additional cost depending upon the model. If energy losses ΔW_{ij} are considered in a classical nodal prices market formulation, then:

$$\Delta C_{ij} = C_{ij} \cdot \frac{\Delta W_{ij}}{W_{ij}} \quad (8.1)$$

Generally, there can be a T&D tariff according to the market model. In this case:

$$\Delta C_{ij} = p_{T\&D} \cdot \Delta W_{ij} \quad (8.2)$$

The process of flow costs distribution is accomplished until flow costs pass across a grid equivalent circuit to output nodes and there are no other cost flows paths. It is worth mentioning, that when the procedure of flow costs allocation is completed, total utility transport costs are exactly equal to a sum of flow costs in output nodes of a grid. The model implies that a total costs for EE is distributed between N nodes and M branches of a grid proportionally to T&D costs. So, while EE is distributed through a grid, the cost per kWh increases.

C. Analysing Renewable Energy flow distribution

The aim of the model applied to RES analysis is to estimate their true integral influence on the nodal prices and prices of electrical energy flowing in a grid. According to *A* Section of the paper the intermittent energy sources to be estimated by integral models, especially if a deep reverse of energy flows is possible in

a distribution. According to *B* Section of the paper, there initial data for energy consumption by load and existing generation is efficient to obtain using meters data. The initial data for the renewables output itself may be based on the scaled retrospective. Otherwise, any forecast output for the period under consideration to be used.

The analysis of the cost for renewables may be done in following ways:

- 1) Most of the manufacturers provide the information about the level of *LCOE* for the particular model of the renewable energy source. It can be used as the initial rough approximation for the considered source.
- 2) Generally, *LCOE* of renewables is a sophisticated function of the output $LCOE=f(W)$ to be matched with the forecasted output [24]-[26].

The algorithm of RES influence estimation includes a two-stage procedure:

- 1) Calculation of the *energy flow distribution*;
- 2) Calculation of the *cost flow distribution*.

The workflow chart of the algorithm is presented in Fig. 1.

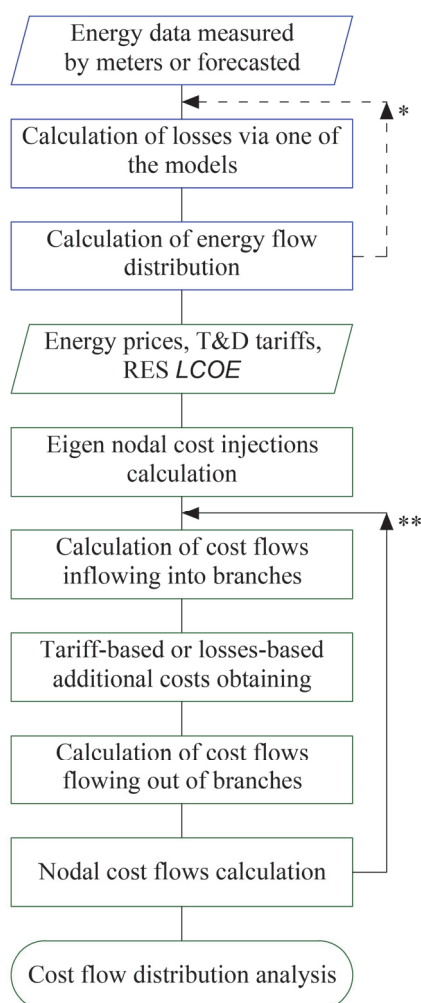


Fig. 2. The two-stage procedure of *energy* and *cost flow* distribution. Notes: *iterative procedure for non-linear losses only; **starts with the dead-end power lines and calculated for a grid until there are no other cost flows paths

In case of the reverse approach, when the required *LCOE* to be obtained depending upon the energy flow distribution, the whole procedure of cost flow distribution turns out to be iterative.

Although the proposed model is insensitive for a number of nodes, general grid observability criteria to be met [13]. Otherwise, in case of a wide RES mix it turns out in equivalent *LCOE* for a set of distinguishing RES that may compromise the efficiency estimation of particular sources. Also a high share of beyond-the-meter RES hides the real cost flow distribution if the output is not detected. Therefore, both kinds of problems to be eliminated by dedicated EE meters providing energy accounting and grid observability in terms of the model.

3. Case Study

The case study is conducted using real-prototype 10 kV distribution grid (Fig. 2). Given the assumption of independent active and reactive flows distribution [11] just active EE flows are presented for the purposes of the clarification. The grid includes both radial and loop circuits. The transmission grid and power system are set as System equivalent at the first node. There are two types of energy consumers: residential households (that also may include some share of commercial and offices) and powerful industrial consumer. It is supposed that the consumer have its embedded beyond-the-meter generation, that's why it is considered as a prosumer. The corresponding energy output surplus is released to the grid during the periods of production shift changes.

Nodal EE values measured by the meters marked by "X" signs in Figure 2. The values for the purpose of clearness are preliminary shown for three periods of the day: off-peak (*a*), semi-peak (*b*) and peak (*c*), correspondingly. The prices for EE are shown in Table I.

Table I. – Nodal electricity prices for basic/corrected renewables *LCOE*

Time	Price, € per MWh			
	Power System (PS)	Industrial Prosumer (IP)	Renewables (Ren)	Residential (Rsid)
Off-peak	150.0	500.0	650.0/644.7	368.5/366.9
Semi-peak	200.0	204.5/204.6	650.0/644.7	433.5/430.8
Peak	675.0	707.4/706.2	650.0/644.7	680.3/676.1
Total	514.5	658.7/657.5	650.0/644.7	517.6/514.5

It is supposed that the System is represented by bulk market typically obtaining the lowest EE price due to scale effect. The tasks for the calculation can be formulated as follows:

- 1) To calculate the integral nodal energy prices taking into account the variability and EE losses;
- 2) To determine the required *LCOE* for the Renewables given the case when the cost for Residential can't exceed the price of the

System' bulk market. This requirement is typical for some energy markets.

Energy flow distribution is calculated by the model presented at 2.A Section of the paper. The resulting energy flow distribution is shown at Figure 2, d. The following features can be noted regarding the energy flow distribution:

- 1) *There's a reverse energy flow in a loop circuit via Ren-IP power line. An attempt to average the flow and use a power flow distribution instead of the energy flow distribution leads to strong unbalances like it is described in Sections 1 and 2.A;*
- 2) *Both consumers supplied by three energy sources establishing different combinations depending on period of the day. An attempt to average the flow and use a power flow distribution instead of the energy flow distribution leads to the embedded generation unaccounted. In addition, in this case market mutual settlements become unclear.*

Cost flow distribution is calculated by the model presented at 2.B Section of the paper. The following features can be noted regarding the energy flow distribution:

- 1) *Due to the deep state diversity the distribution of the nodal prices is not evident before the cost flow calculation.*
- 2) *Weighted EE cost of 514,5 €/MWh purchased from power system is closer to the peak price of 675 €/MWh;*
- 3) *Energy prosumer have the resulting cost of 658,7 €/MWh. There's a potential for increasing*

its embedded generation output due to the fact that there's a gap between the generation price of 500 €/MWh and much more expensive EE purchased from the grid;

- 4) *The cost of EE losses is only 2,1 % although the share of EE losses is 3,1 %;*
- 5) *The EE cost for Residential of 517,6 €/MWh is close to the power system price of 514,5 €/MWh, although there are 2 energy sources much closer than power system.*

The influence of Renewables' *LCOE* is not the predominant due to the fact that there's also some share of EE to Residential distributed from Prosumer and System via the loop circuit. The solution of the (4)-(7) linear formulation by any solver gives the result that Renewables' *LCOE* decrease to 644,7 €/MWh provides the cost for Residential of 514,5 €/MWh not exceeding the price of the System market. The corrected prices for this case are shown in Table I after the slash signs.

4. Conclusion

A two-stage procedure for estimation of energy flows and cost flows in a grid is presented. Both stages are performed based on the branch-flow model. It has the following features.

1. Unlike power flow distribution describing the instant point of time, energy flow distribution for any operation duration deals with the integral values of the flows. This is of great importance for the deeply varying output profiles of the intermittent renewables.

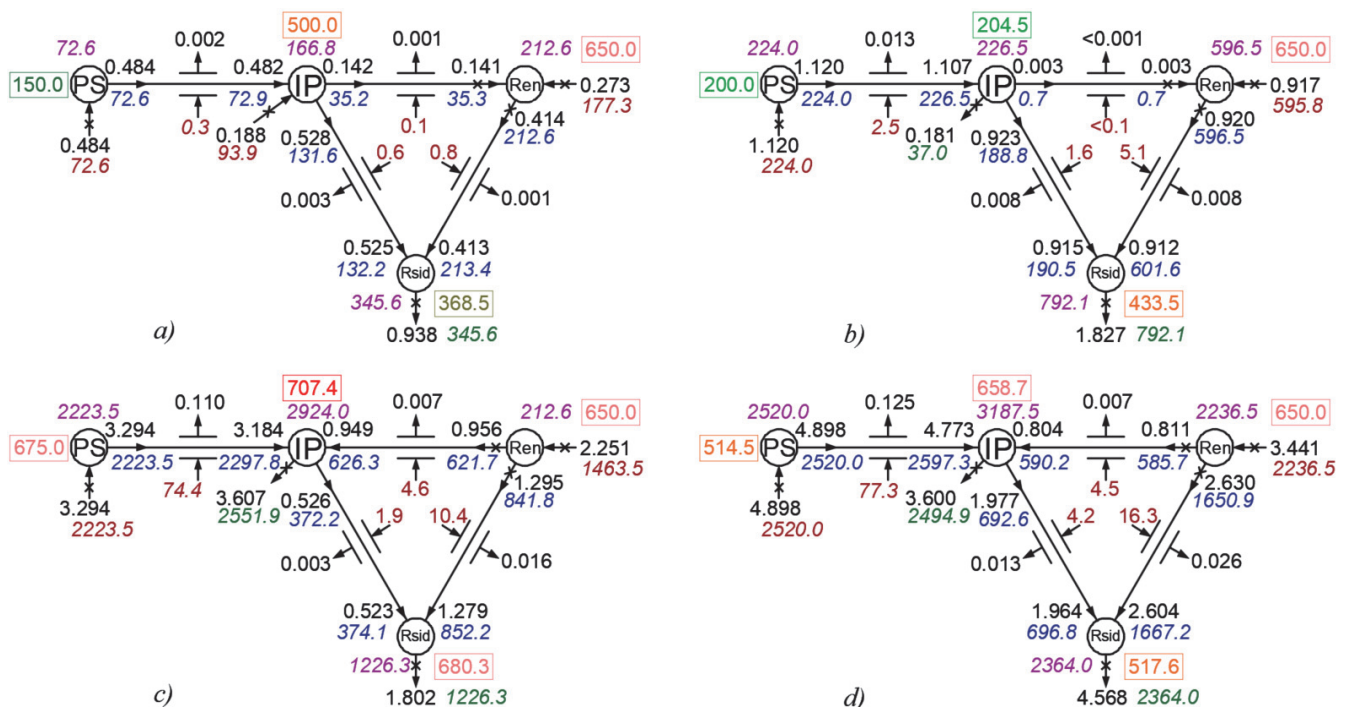


Fig. 2. Energy flow distribution and cost flow distribution per off-peak (a), semi-peak (b), peak (c), and total per day (d). Legend: electricity flow in MWh, nodal cost injection in €, nodal cost output in €, branch cost flow in €, nodal costs in €, [nodal price] in €/MWh. The values of energy losses are shown with 0.001 accuracy and may not coincide due to the rounding

2. The model provides the direct utilization of electric energy meters data available in a grid for well-fitted estimation.

3. The approach presented is essential for locating the particular consumers of the renewable energy in terms of a grid's deep state and circuit diversity as well as for analyzing the influence of a renewable energy for electricity prices, and estimating the necessary renewables *LCOE* levels.

4. The model is sensitive for the duration of power lines and substation buses disconnection, so these events to be detected by Smart Meters directly or as energy flow absence.

Further investigations regarding the topic may include the optimization issue for renewables placement. It may be carried out using different criteria, like energy losses costs increments (penalty factors) and feed-in tariffs. Both criteria requires a modification of the two-stage procedure presented in the paper.

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